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INSTRUCTION MANUAL FOUR (4) CHANNEL HETERODYNE UNIT,(U)
APR 69 G M HOWARD, T F BALL

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INSTRUCTION MANUAL

FOUR (4) CHANNEL HETERODYNE UNIT

by G. M. Howard ~~and~~ T. F. Ball

San Diego, California

SUBPROJECT NO. SF 11 121 100

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ILLUSTRATIONS (Continued)

SECTION 1

1.0 GENERAL INFORMATION

1.1 Purpose and Scope

This publication contains a general description of, and installation and operating instructions for the Four (4) Channel Heterodyne Unit designed and constructed at Naval Undersea Warfare Center, San Diego, California. This equipment was developed to meet the performance requirements of Sections 3.5 and 3.6 of NEL Specification No. 3180-66-6 (Active Sonar Data Analysis and Conversion System).

A general description of the electrical and physical characteristics, and a basic description of the principles of operation of the unit are presented in Section 1. Section 2 describes the procedures for initial setup and installation of the unit. Section 3 describes the operating procedure. The detailed theory of operation of the Heterodyne Unit is covered in Section 4. Section 5 covers, in detail, the calibration and trouble shooting procedure for use in the event of equipment failure. Section 6 consists of a series of drawings which are included in this manual for clarification of the subject matter. Section 7 is a mathematical description of heterodyning abstracted from NUWC TN-32, "A Balanced, Switching Audio Modulator With High Carrier Rejection" by G. M. Howard. Section 8 is an abstract of NEL Specification No. 3180-66-6, which describes the original requirements for the Heterodyne Unit.

1.2 Introduction to the Equipment

The Four (4) Channel Heterodyne Unit is a solid-state instrument, each channel of which accepts an analog input in the audio range, and, by performing time-multiplication against a square wave, shifts the amplitude and phase characteristics of the input to a different set of center frequencies. The new center frequencies are determined by the signal's original center frequency and the fundamental and odd harmonic frequencies of the square wave. From this spectrum, the desired band can be isolated by the appropriate filtering.

1.3 Requirements of NEL Specification No. 3180-66-6

As development of the Heterodyne Unit proceeded, it became clear that significant improvements could be made in the functional organization of the equipment. Therefore, the Unit has been designed to operate independently, with filters and a local oscillator to be added externally. The reasons for this design are as follows:

1. Several brands of tunable filters which could meet the requirements of the NEL Specification were found to be readily available.

2. Filter requirements can vary considerably depending on the particular application; hence, it is desirable to be able to substitute filters easily.

3. Inclusion of a simple threshold and squaring circuit in the Heterodyne Unit itself allows a sine wave instead of a square wave to be supplied to the Unit. Therefore, degradation of the square wave through the interconnection is avoided.

The Heterodyne Unit has been designed to meet all performance requirements of the NEL Specification (see Section 8, Appendix II) if suitable choices of filters and local oscillator are made. Filter recommendations are discussed in Section 3. The choice of a local oscillator will depend on the frequency stability required for a given application.

1.4 Technical Specifications

Signal Input	
Maximum Input Voltage	**2.4 volts p-p**
Input Impedance	**10 K ohms**
Frequency Range	**500 Hz to 20 kHz**
Oscillator Input	
Minimum Input Voltage	**1.0 volts rms**
Input Impedance	**2.5 K ohms min.**
Frequency Range	**500 Hz to 40 kHz**
Rejection (unfiltered)	
Switching Frequency (f_h)	**>45 dB r.f.s.**
Signal Frequency (f_s)	**>45 dB r.f.s.**

Linearity	±.05% r.f.s., 50 Hz to 25 kHz
Noise (narrow band)	-60 dB r.f.s.
Insertion loss (adjustable)	nominally 0 dB
Packaging	7" × 19" rack mount
Power Requirements	115 volts, 60 Hz

REVERSE SIDE BLANK

SECTION 2

2.0 INSTALLATION

2.1 General

This section describes the installation procedures and equipment necessary for checkout and calibration of the Four (4) Channel Heterodyne Unit.

2.2 Mounting

The unit is designed to be mounted in a standard 19 inch rack requiring 7 inches of vertical space. To prevent scratching the front panel, nylon filler washers may be placed under the rack mounting screws.

2.3 Wiring Connectors

An outline drawing of the unit in Section 6 of this manual shows the location of the 40 pin connector used for the signal and oscillator inputs and the signal outputs.

2.4 Primary Power

The Four (4) Channel Heterodyne Unit operates on 105-125 volt AC, 50 to 400 cycle single phase. An integral ON-OFF switch is present on the front panel. The unit is protected by a 2-amp, slo-blow fuse readily accessible at the rear of the cabinet.

2.5 Signal Inputs and Outputs

The signal and oscillator inputs and signal outputs for each channel of the unit are wired to the 40-pin Connector on the rear panel as shown in Section 6. The external system ground should be connected to the ground pin of this connector.

2.6 Additional Equipment

For proper operation of the Four (4) Channel Heterodyne Unit an accurately adjustable frequency source for use as an external oscillator and four tunable low pass filters with which to select the desired band of heterodyned frequencies are required.

SECTION 3

3.0 OPERATION

3.1 General

Refer to Section 6 for proper connection information. Insure that the proper fuse is in its fuse holder and turn power to ON. After a warm-up period of 20 minutes, check the voltages at the power supply test points on the front panel. If the unit is properly connected and the voltages are correct, the Four (4) Channel Heterodyne Unit is ready for operation.

3.2 Selection of Local Oscillator Frequency

In normal operation the input signal will be down-shifted in frequency to a new center frequency

$$f_s' = \frac{BW}{2} + 50$$

where BW is the bandwidth of the input signal expressed in Hertz. Since f_s' can also be expressed as the difference between the original center frequency, f_s, and the heterodyne frequency, f_h, this gives the equality:

$$f_s - f_h = \frac{BW}{2} + 50$$

or

$$f_h = f_s - \left(\frac{BW}{2} + 50\right)$$

As is explained in Section 4.5, <u>the actual frequency by which the input signal is heterodyned</u>, f_h, <u>is one-half that of the frequency of the external oscillator</u>, f_o. Therefore, f_o can be selected by applying the following equation:

$$f_o = 2f_h = 2f_s - (BW + 100)$$

This will result in the original spectrum being shifted to a new center frequency, f_s', which has been chosen to place the lower band-edge of the original spectrum at 50 Hz (see figure 1). Example: Assume a signal with a center frequency of 1000 Hz and a bandwidth of 300 Hz. The new center frequency should be

$$f_s' = \frac{BW}{2} + 50 = 200 \text{ Hz}$$

This requires a heterodyning frequency:

$$f_h = f_s - \left(\frac{BW}{2} + 50\right) = 1000 - 200 = 800 \text{ Hz}$$

or a local oscillator frequency of

$$f_o = 2f_s - (BW + 100) = 2000 - 400 = 1600 \text{ Hz}$$

3.3 Selection of Filter Cutoff Frequency

To eliminate the higher order harmonics of the output spectrum of each heterodyne channel, it is necessary to filter the output with a low pass filter. The filter selected for this use is the Dytronics Model 721 Digital-data Filter with switch selectable attenuation rates of 12, 24, and 36 dB/octave. For most signals, the 36 dB/octave attenuation rate should be used together with a cutoff frequency equal to 1.25 times the highest frequency of interest (figure 2). This can be expressed as $f_c = 1.25\ (BW + 50)$ Hz.

Therefore, for example in Section 3.2, with $f_s' = 200$ Hz and BW = 300 Hz, the cutoff frequency should be set at $f_c = 1.25\ (350) = 435$ Hz.

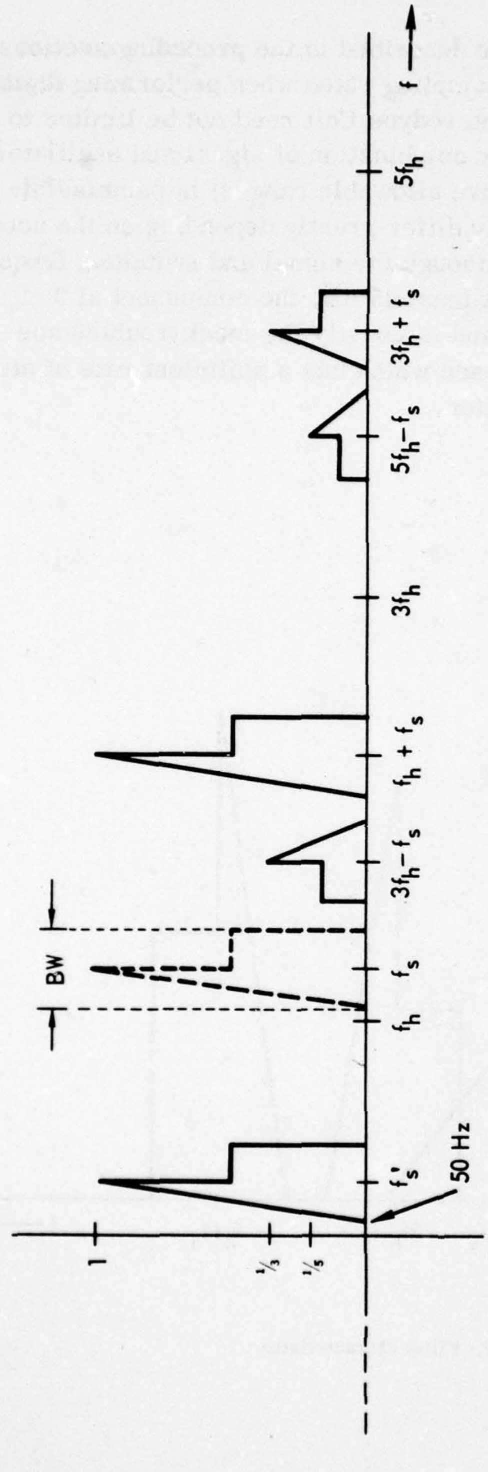


Figure 1. Output spectrum of a single H.U. channel.

3.4 General Heterodyning Operation

The heterodyning procedure described in the preceding sections is used primarily to permit lower sampling rates when performing digital operations on the signal. The Heterodyne Unit need not be limited to this particular type of operation. Any combination of signal and oscillator frequencies (within their respective allowable ranges) is permissible; however, filter requirements may differ greatly depending on the actual choices of these frequencies. Although the signal and switching frequency components will be rejected by at least 45 dB, the component at $3f_h - f_s$ will only be rejected about 9 dB and is usually the most troublesome component. A filter must be chosen which has a sufficient rate of attenuation to achieve the desired rejection.

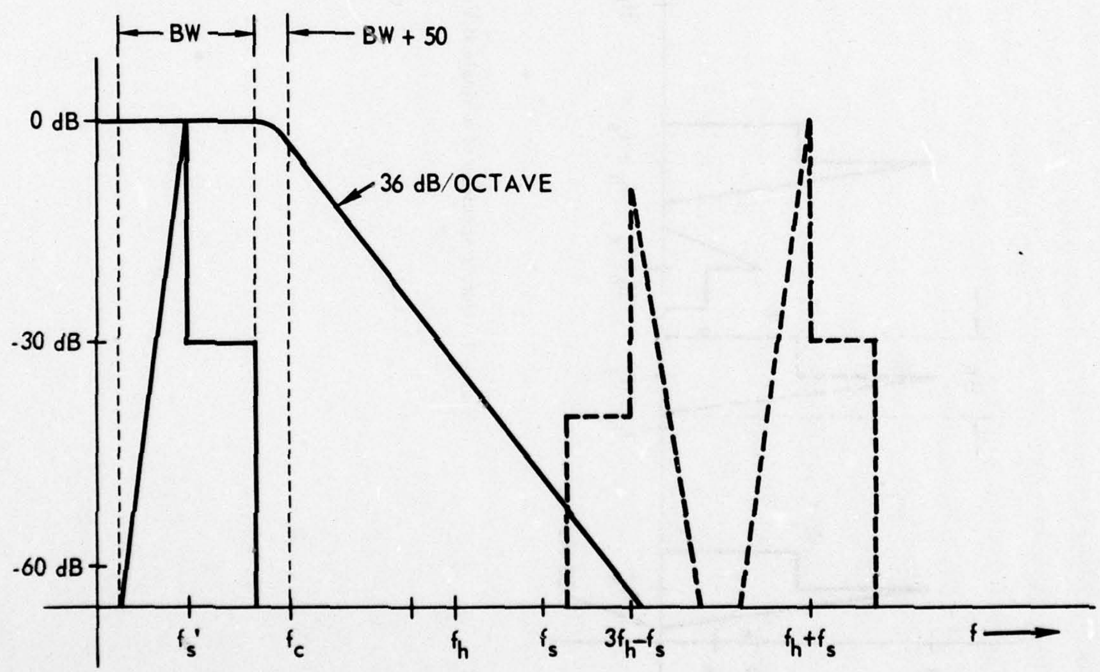


Figure 2. Filter characteristic.

SECTION 4

4.0 THEORY OF OPERATION

4.1 Introduction

A general and brief description of the overall purpose of the Heterodyne Unit was given in Section 1 of this manual. This section will separate the unit into its individual components and explain the operation of each.

4.2 Functional Description

Figure 3 is a block diagram of a single channel of the Four (4) Channel Heterodyne Unit. Each channel is constructed on one circuit board as shown in Section 6.

Basically, the modulator consists of an inverting amplifier with a gain of -1, a non-inverting amplifier with a gain of +1, a transistor switch and a switching waveform shaper whose input is a sine wave from an external oscillator and whose output is a square wave at one-half the oscillator frequency.

The outputs of the amplifiers are selected by the transistor switch at a rate determined by the output of the switching waveform shaper. The resulting waveform is a realization of the time multiplication of a square wave with the input signal (see Appendix II for mathematical description of process). It is then amplified in the output amplifier to condition the output such that the desired frequency components are equal in amplitude to those of the input signal.

4.3 Inverting Amplifier

The inverting amplifier is a Philbrick P65A amplifier connected with a feedback network as shown in figure 4. The feedback equation for an operational amplifier connected in this configuation is

$$\frac{E_o}{E_i} = \frac{-R_f}{R_i} \quad \text{or} \quad E_o = \frac{-R_f}{R_i} E_i$$

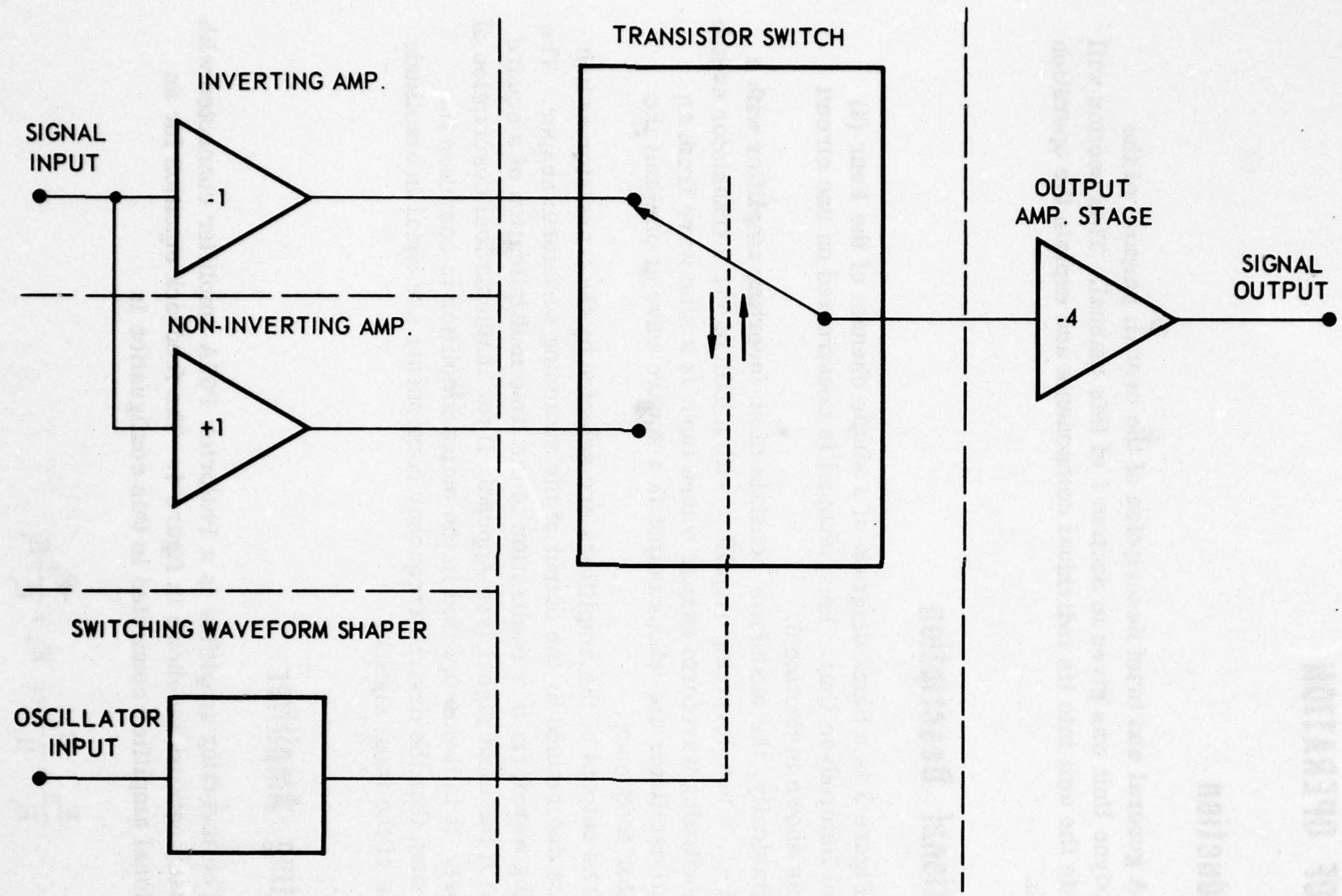


Figure 3. Block diagram of a single H.U. channel.

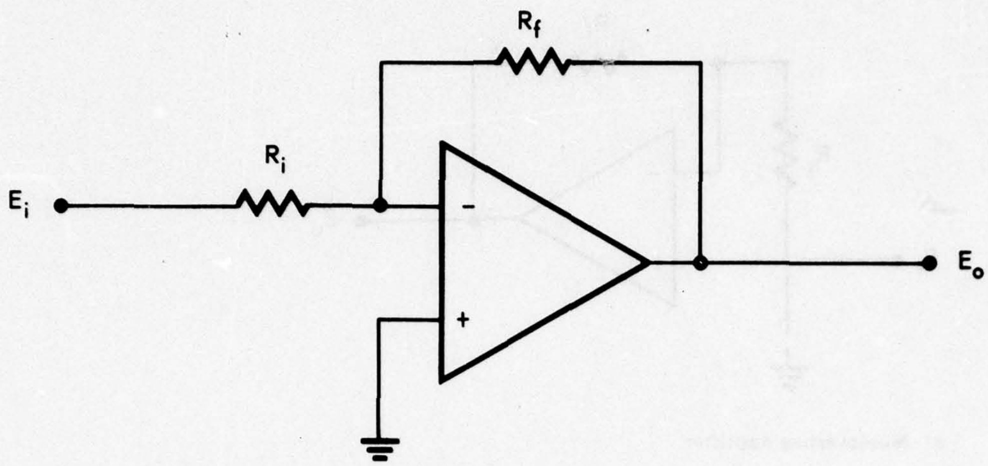


Figure 4. Inverting amplifier.

When the potentiometers in the feedback branch are adjusted so that

$$R_f = R_i$$

This reduces to

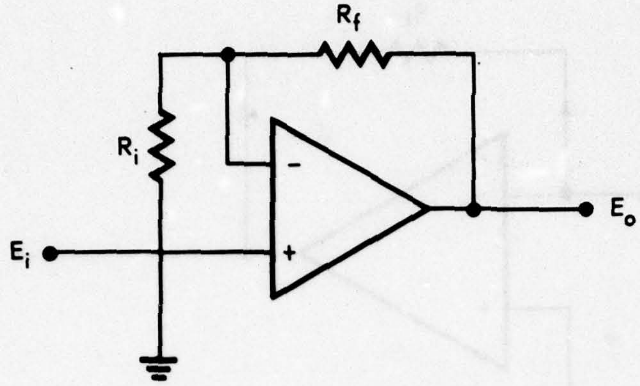
$$E_o = -E_i$$

In the actual circuit used in the Heterodyne Unit, R_f is replaced by two potentiometers which provide Coarse and Fine Gain adjustment.

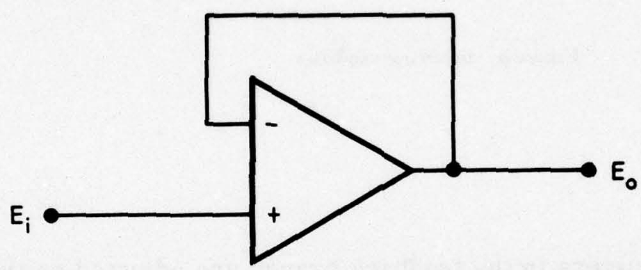
4.4 Non-Inverting Amplifier

The non-inverting amplifier is another P65A operational amplifier connected as a special case of the feedback network shown in figure 5a. The feedback equation for this network is

$$\frac{E_o}{E_i} = \frac{R_i + R_f}{R_i}$$



a) Non-inverting amplifier



b) Special case of the non-inverting amplifier.

Figure 5. Non-inverting amplifier and special case of the non-inverting amplifier.

or

$$E_o = \frac{R_i + R_f}{R_i} E_i$$

For the non-inverting amplifier used in the modulator, figure 5b, R_i is an open circuit and R_f is a short circuit; i.e., $R_i = \infty$, $R_f = 0$, so that the equation reduces to

$$E_o = E_i$$

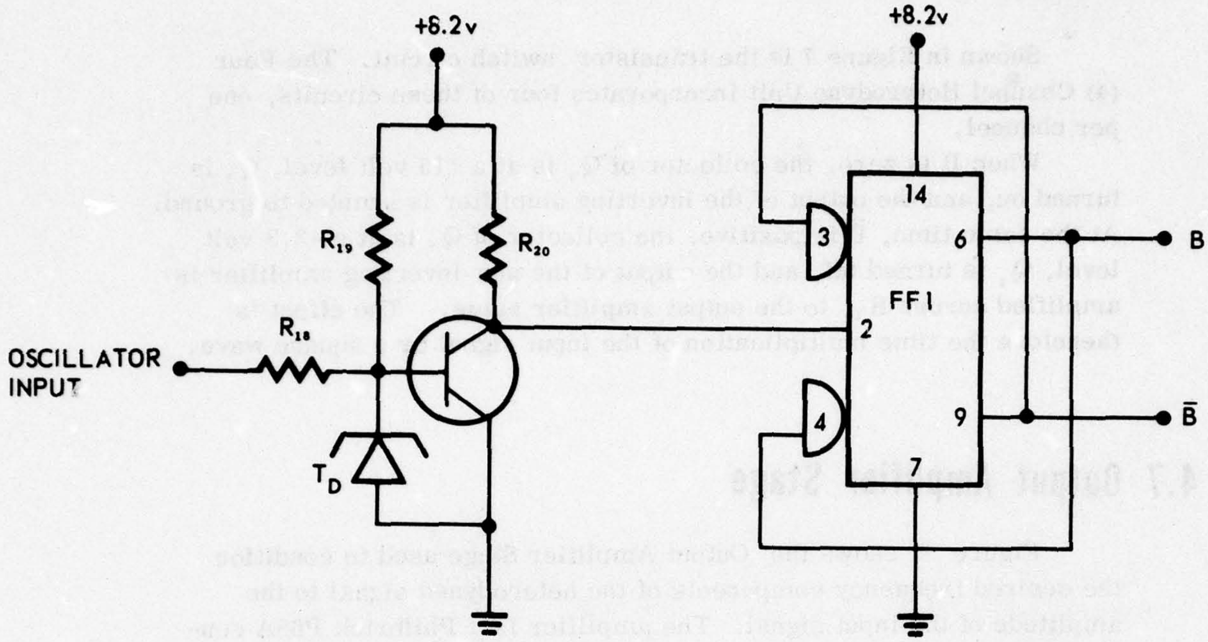


Figure 6. Switching waveform shaper.

4.5 Switching Waveform Shaper

Shown in Figure 6 is the circuit for the Switching Waveform Shaper. It consists of a thresholding circuit whose output acts as a clock pulse for a toggle action I.C. flipflop. The threshold can be changed by varying R_{18}.

The outputs of the flipflop, B and $\bar{B}$, are used as the gating signals to the transistor switch. Since the flipflop is connected as a toggle type, it will change state each time Q5 thresholds. Therefore, the frequency of the square wave output of B and $\bar{B}$ will be one-half that of the sine wave input from the external oscillator.

4.6 Transistor Switch

Shown in Figure 7 is the transistor switch circuit. The Four (4) Channel Heterodyne Unit incorporates four of these circuits, one per channel.

When B is zero, the collector of Q_3 is at a +15 volt level, Q_1 is turned on, and the output of the inverting amplifier is shunted to ground. At the same time, $\bar{B}$ is positive, the collector of Q_4 is at a -3.3 volt level, Q_2 is turned off, and the output of the non-inverting amplifier is amplified across R_{16} to the output amplifier stage. The effect is therefore the time multiplication of the input signal by a square wave.

4.7 Output Amplifier Stage

Figure 8 shows the Output Amplifier Stage used to condition the desired frequency components of the heterodyned signal to the amplitude of the input signal. The amplifier is a Philbrick P65A connected as an inverting amplifier with a gain of approximately -4.

4.8 Power Supplies

The primary DC power supplies in the unit consist of two Acopian 15 volt supplies, Model 15D75A, one wired for +15 volts and the other for -15 volts. The 8.2 volts required by the switching waveform Shaper and the -3.3 volts for the transistor switch are supplied by the zener regulator circuits shown in Figures 9a and 9b. Each board includes one of each of the circuits shown.

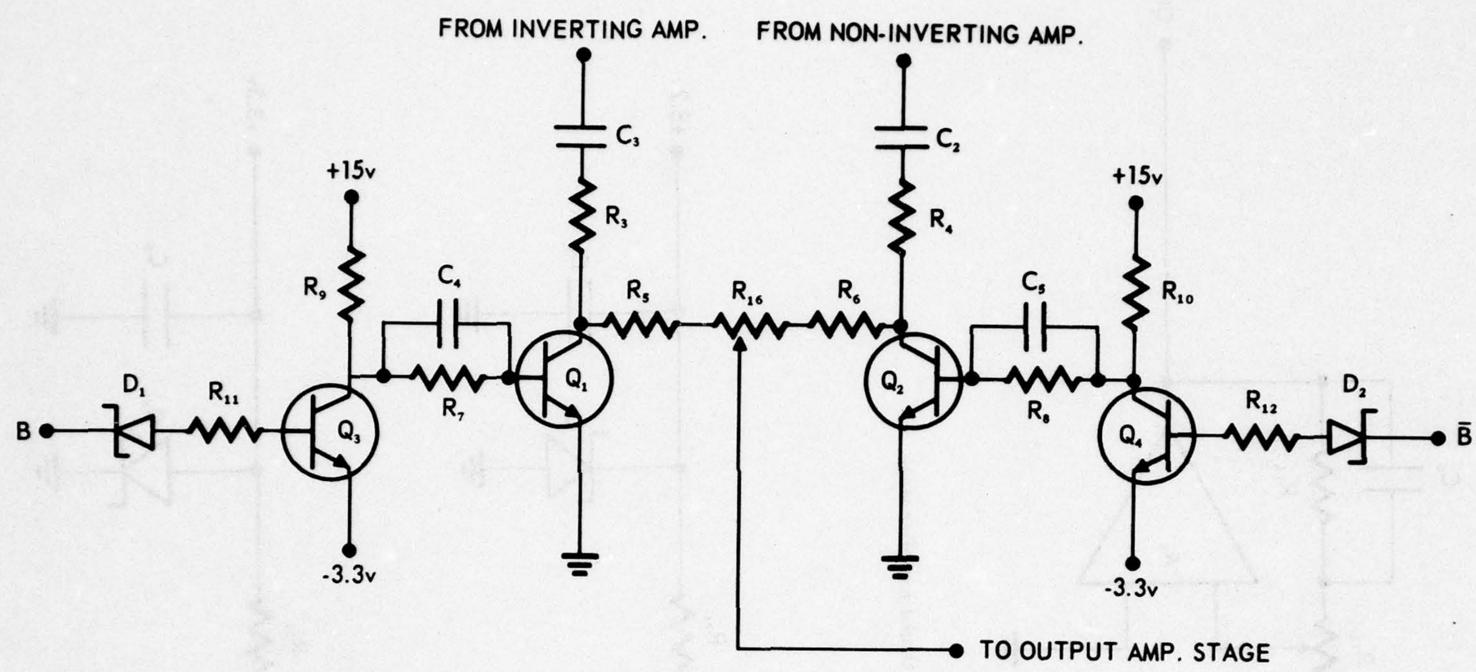


Figure 7. Transistor switch.

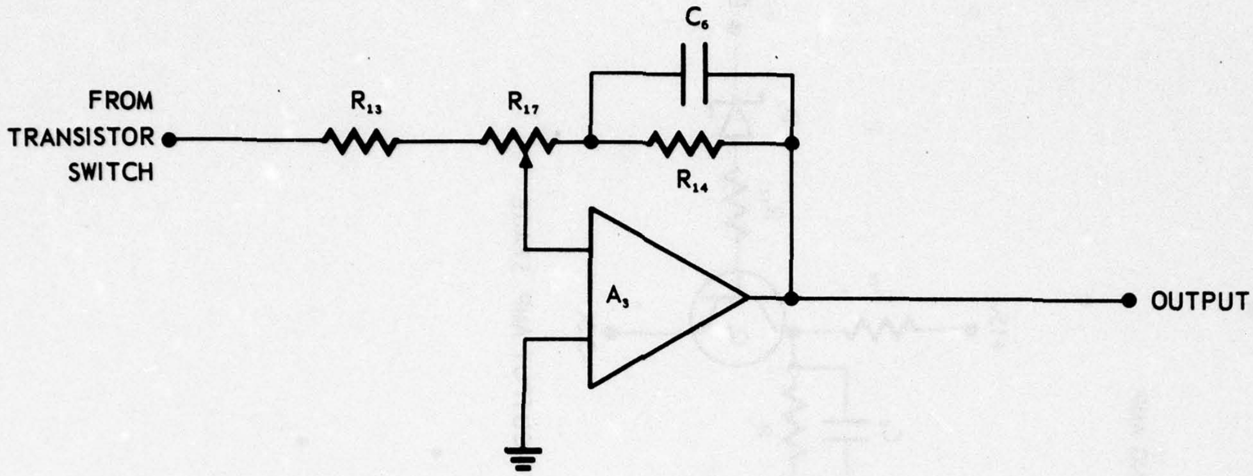
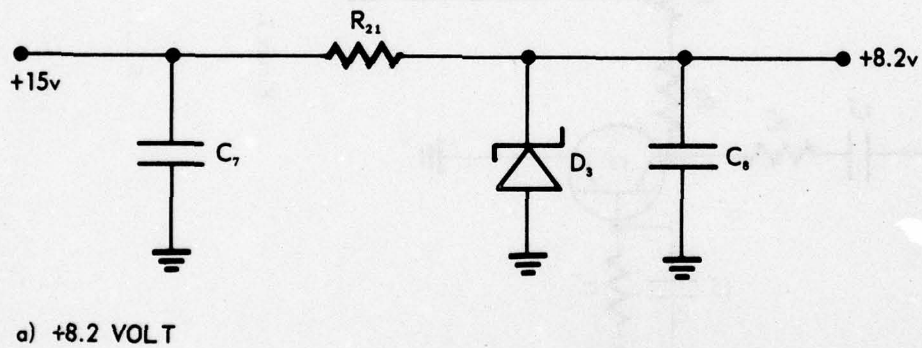


Figure 8. Output amplifier stage.



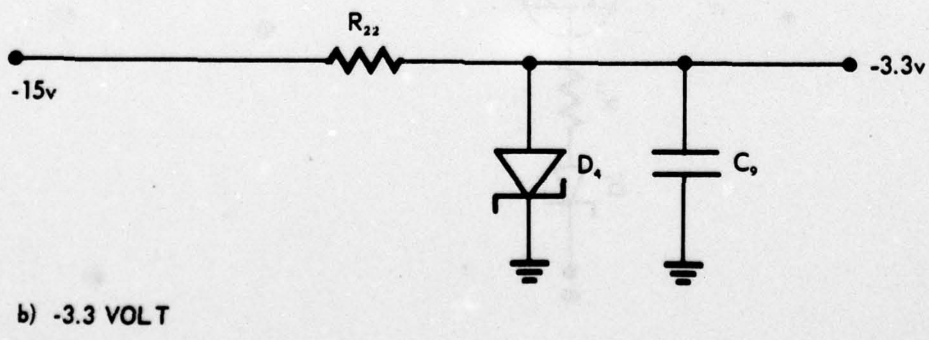


Figure 9. Power supplies.

SECTION 5

5.0 CALIBRATION PROCEDURES

5.1 Calibration Equipment

Equipment needed for calibration consists of the following:

1. VTVM (HP 410C or equivalent)

2. Two stable oscillators such as the HP 241A Pushbutton Oscillator or equivalent.

3. Wave Analyzer such as the General Radio Model 1900A or equivalent.

5.2 General Calibration Procedure

Sections 5.3 through 5.6 cover each of these steps in detail. Allow twenty minutes warmup before calibration.

1.	Adjust +15v	Section 5.3
2.	Adjust -15v	
3.	Adjust Balance Pot (R_{16})	Section 5.4
4.	Adjust Gain Pots (R_2, R_{15})	Section 5.5
5.	Adjust Output Gain Pot (R_{17})	Section 5.6

5.3 Power Supply Calibration

Calibration of the two Acopian 15 volt supplies is a fast and simple procedure. Test points are located on the front panel of the unit as shown in Section 6 and the trim pots are on the sides of the supplies.

1. Using the VTVM, check the +15 volt test point.

2. Adjust the trimpot on the rear supply for +15 volts DC.

3. Connect the meter to the -15 volt test point.

4. Adjust the trimpot on the front supply, using the access hole cut in the front panel for this purpose for -15 volts DC.

5.4 Switching Frequency Rejection Adjustment

To attain maximum rejection of the heterodyne frequency, the following adjustment procedure should be used:

1. Connect one of the oscillators, set at 1.6 kHz, 1 volt RMS, to the oscillator input of the channel to be calibrated and ground the signal input.
2. Connect the wave analyzer to the output and tune to 800 Hz (fine tune for maximum indication).
3. Adjust the balance pot, R_{16}, (see Section 6 for card layout) for maximum rejection of the 800 Hz component.
4. Test points on the front of the unit may be used for input and output.

5.5 Signal Frequency Rejection Adjustment

To attain maximum rejection of the input signal, the equipment configuration set up in Section 5.4 should be retained and the following procedure used:

1. Unground the channel signal input and connect the second oscillator, set at 1 kHz, 2.0 volts p-p
2. Tune wave analyzer to 1 kHz (fine tune for maximum indication)
3. Adjust the Coarse Gain pot, R_2, and the Fine Gain pot, R_{15}, (see Section 6) for maximum rejection of the 1 kHz signal.

5.6 Output Amplifier Stage Calibration

To adjust circuit for zero insertion loss, the equipment configuration described in Sections 5.4 and 5.5 is retained and the following procedure used.

1. Tune wave analyzer to 200 Hz (for f_s = 1 kHz and f_h = 800 Hz).

2. Adjust Output Gain pot R_{17} (see Section 6), so that the output at 200 Hz is equal in level with the signal input.

3. Channel calibration is now complete.

5.7 Filter Requirements

With f_s and f_h set at the desired frequencies, connect a Wave Analyzer to the output of the Heterodyne Unit and obtain an amplitude versus frequency plot of spurious components in the frequency band of interest. The filter requirements (attenuation slope) necessary to achieve the desired rejection of unwanted components can be determined from this plot.

5.8 Selection of Matched Switching Transistors

For best operation of the circuit, the close matching of the two 2N708 switching transistors, Q1 and Q2, is necessary. If the need arises to replace this pair, the following procedure should be used for the selection of a matched set. A transistor curve tracer should be set up in the following configuration:

1. Collector Sweep:

   a. Peak volts = 2 volts

   b. Dissipation Resistor = 500 ohms

2. Base Step Generator:

   a. Series Resistor = 15 K ohms

   b. Step Selector = .01 ma/step

   c. 4 step/family

3. Scales:

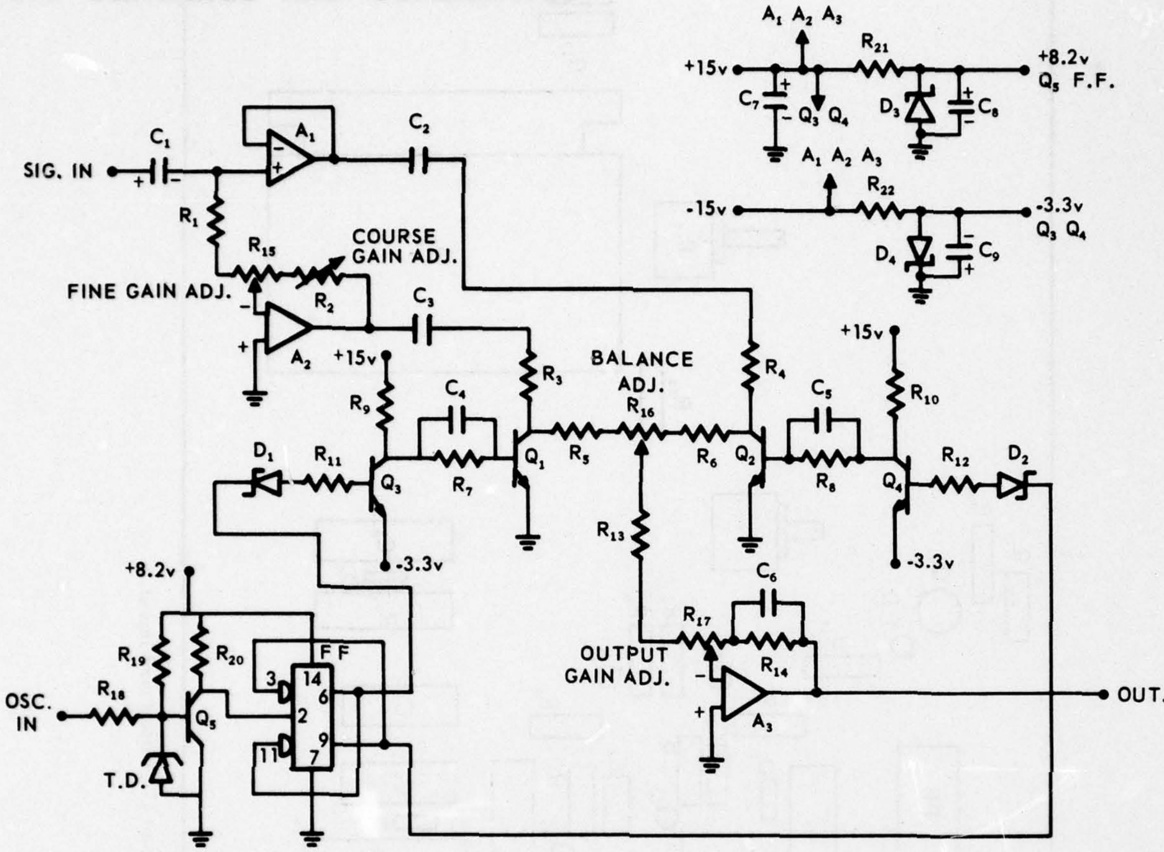
   a. Vertical = 0.2 ma/div

   b. Horizontal = 0.2 v/div.

After comparison of the curves of several 2N708's, a pair which match with a $\Delta I_c \leq 20\ \mu a$ and a $\Delta V_{ce} \leq 20mv$ should be selected. If the circuit fails to meet specifications after installation of the new pair of transistors and recalibration, attempt reversing position of transistors before searching for a new pair.

SECTION 6

6.0 DRAWINGS AND SCHEMATICS



A_1, A_2, A_3	- Philbrick P65A	R_{20}	- 5.1 KΩ
C_1	- 10μfd, 35v, 20%	R_{21}	- 180Ω 1 watt
C_2, C_3, C_7, C_8, C_9	- 15μfd, 35v, 20%	R_{22}	- 200Ω 2 watt
C_4, C_5	- 10pfd, glass, 5%	Q_1, Q_2	- 2N708 - matched pair
C_6	- 20pfd, glass, 5%		(see section 5.8)
R_1	- 8.1 KΩ	Q_3, Q_4	- 2N708
R_2	- 10 KΩ pot	Q_5	- 2N1304, GE
R_3, R_4	- 1.1 KΩ 1%	D_1, D_2	- 1N755A, ZENER
R_5, R_6	- 9.1 KΩ	D_3	- 1N756A, ZENER
R_7, R_8	- 15 KΩ 1%	D_4	- 1N746A, ZENER
R_9, R_{10}, R_{11}, R_{12}	- 1.1 KΩ	T.D.	- 1N2929A, TUNNEL DIODE
R_{13}	- 56 KΩ	F.F.	- MC845P
R_{19}	- 220 KΩ		
R_{15}	- 500Ω pot		
R_{16}	- 5 KΩ pot		
R_{17}	- 25 KΩ pot		
R_{18}	- 2.7 KΩ		
R_{19}	- 15 KΩ		

ALL RESISTORS ARE ½ WATT, 5% UNLESS OTHERWISE SPECIFIED.

ALL POTENTIOMETERS ARE LINEAR COMPOSITION.

Figure 10. H.U. channel schematic.

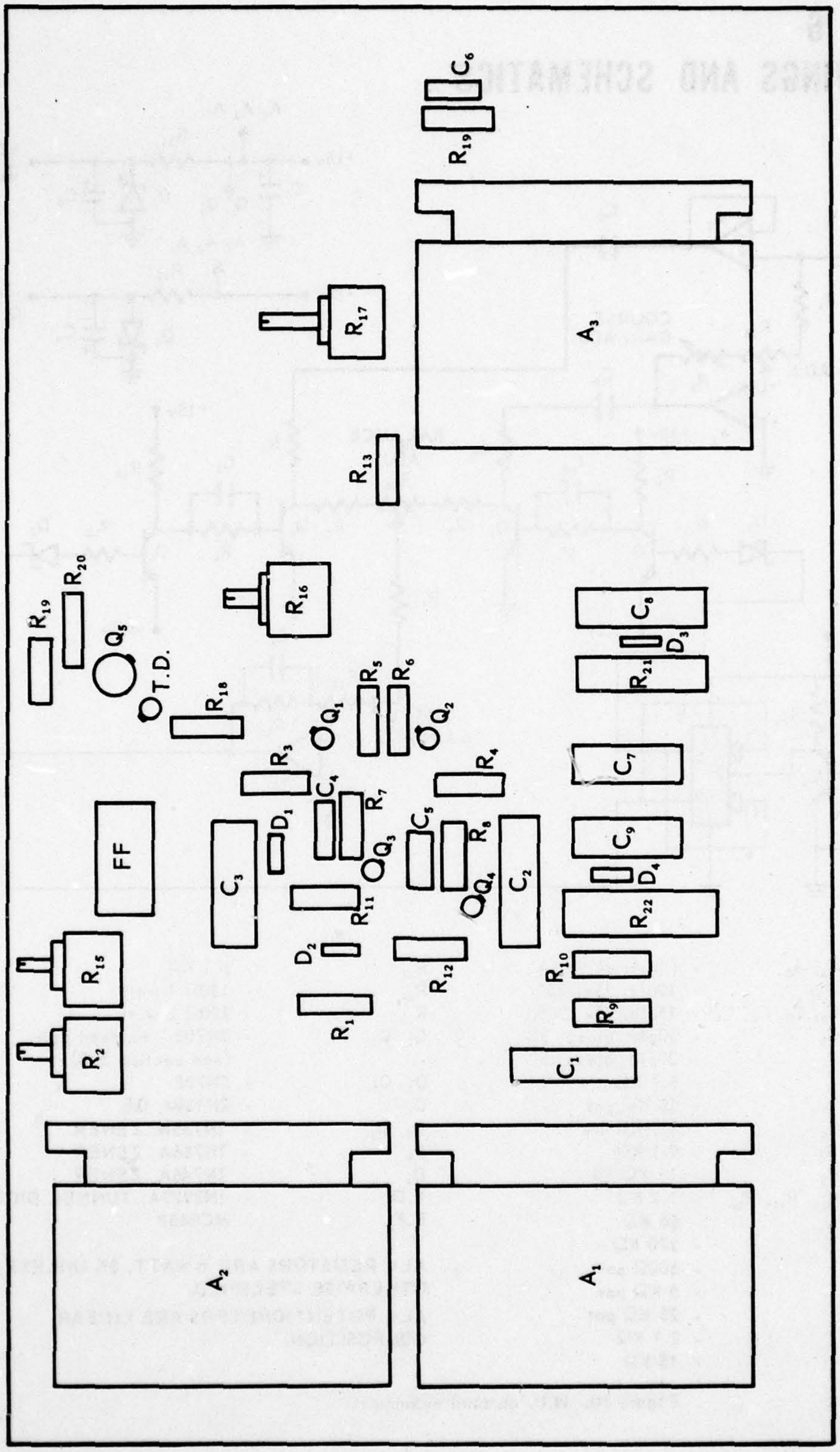


Figure 11. Circuit card layout.

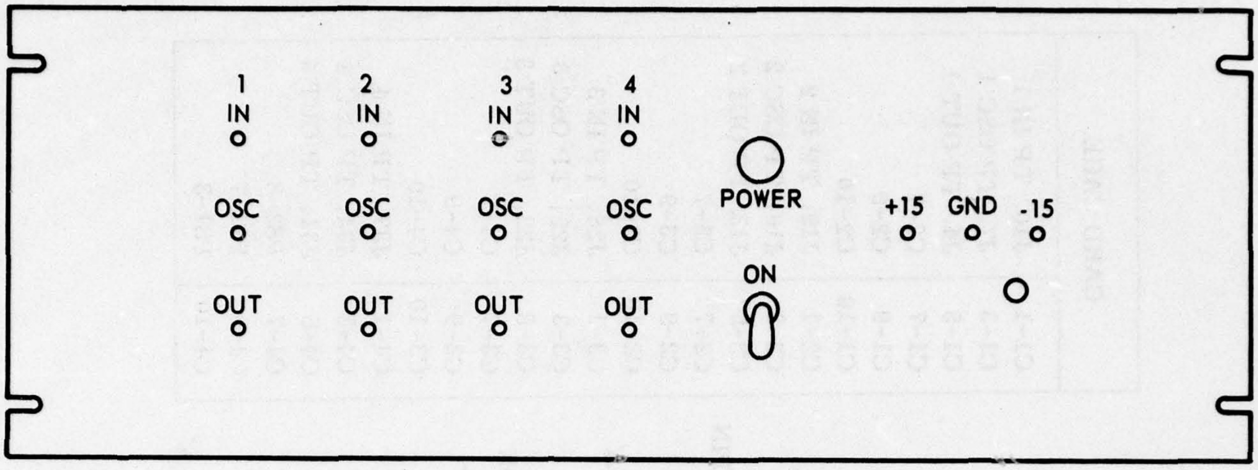


Figure 12. Front panel layout.

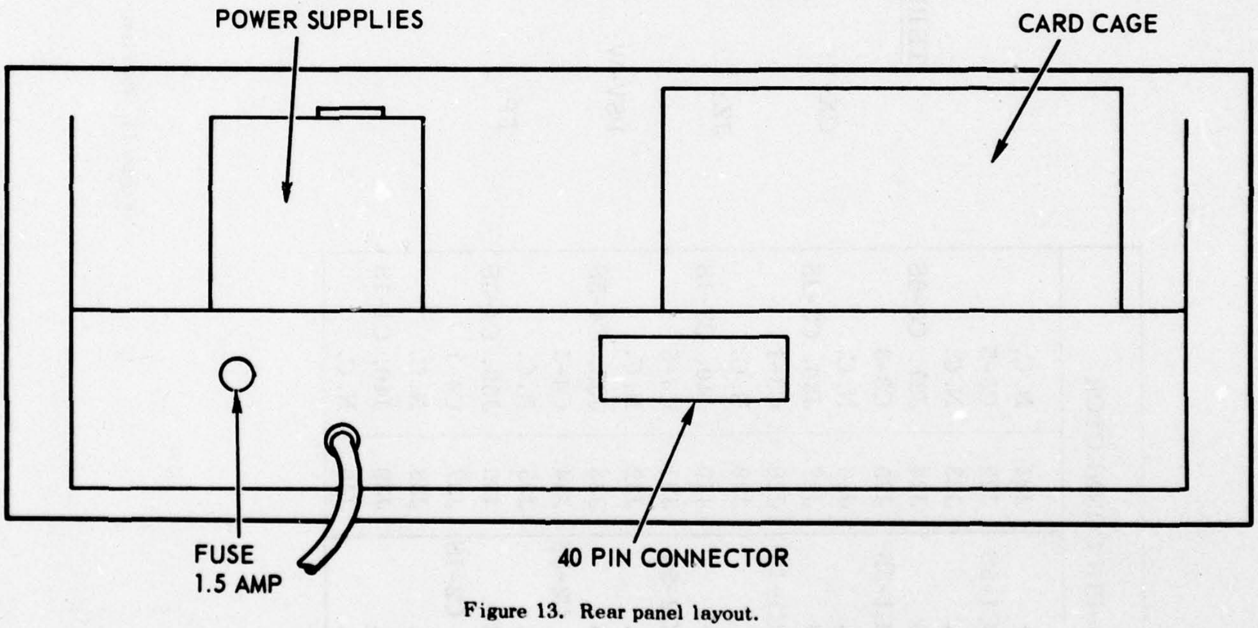


Figure 13. Rear panel layout.

40-PIN CONNECTOR			
J1	GND	J21	N. C.
J2	J1, C1-5S	J22	C3-5
J3	N. C.	J23	N. C.
J4	C1-5	J24	J27, C3-5S
J5	J2, C1-3S	J25	C3-3
J5	N. C.	J26	N. C.
J7	C1-3	J27	J30, C3-3S
J8	J5, C1-1S	J28	C3-1
J9	N. C.	J29	N. C.
J10	C-1-1	J30	J40, C3-1S
J11	J1, C2-5S	J31	C4-5
J12	N. C.	J32	N. C.
J13	C2-5	J33	J36, C4-5S
J14	J11, C2-3S	J34	C4-3
J15	N. C.	J35	N. C.
J16	C2-3	J36	J39, C4-3S
J17	J14, C2-1S	J37	C4-1
J18	N. C.	J38	N. C.
J19	C2-1	J39	J40, C4-1S
J20	N. C.	J40	N. C.

TERMINOLOGY

CX-Y: CARD #X, PIN #Y

JZ: PIN #Z ON 40-PIN CONNECTOR

PSV-W: POWER SUPPLY #V, PIN #W

TP: TEST POINT ON FRONT PANEL

CARD CAGE	
C1-1	J10, TP IN 1
C1-3	J7, TP OSC 1
C1-5	J4, TP OUT 1
C1-7	C2-7
C1-9	C2-9
C1-10	C2-10
C2-1	J19, TP IN 2
C2-3	J16, TP OSC 2
C2-5	J13, TP OUT 2
C2-7	C3-7
C2-9	C3-9
C2-10	C3-10
C3-1	J28, TP IN 3
C3-3	J25, TP OSC 3
C3-5	J22, TP OUT 3
C3-7	C4-7
C3-9	C4-9
C3-10	C4-10
C4-1	J37, TP IN 4
C4-3	J34, TP OSC 4
C4-5	J31, TP OUT 4
C4-7	PS2-8
C4-9	PS1-7
C4-10	PS1-3

Figure 14. Wire list.

SECTION 7

7.0 APPENDIX 1: A BALANCED AUDIO SWITCHING MODULATOR-NUWC TN32

7.1 FOREWORD

This memorandum describes a balanced modulator with high linearity and high carrier rejection for the purpose of up or down shifting the spectrum of an audio signal. The memorandum has been prepared because it may be of interest to a number of people here at NUWC and NELC and possibly to a few people or activities outside of NUWC and NELC. It should not be construed as a formal report as its only function is to present, for the information of others, a small portion of the work being done in the area of signal conditioning for A to D conversion and signal analysis.

7.2 Problem

Develop a balanced modulator with high linearity and high carrier rejection for the purpose of up or down shifting the spectrum of an audio signal.

7.3 Results

A circuit has been developed which will provide better than 30 dB of carrier rejection while up or down shifting the spectrum to the desired values.

7.4 Administrative Information

Work was performed by members of the Signal Recognition Division under SF-101-03-16, Task 8132 (NUWC E1-11).

The basic design of the modulator was developed by L. R. Weill. Circuit design and testing was performed by the author, working in conjunction with Mr. Weill.

7.5 Symbols

A	The sinusoidal input waveform.
$\bar{A}$	The waveform which is the complement of A.
B	The square wave switching waveform.
V_o	The output waveform.
K	A constant scaling factor.
$A(t)$, $\bar{A}(t)$, $B(t)$, $V_o(t)$	The value of the indicated waveform at time t.
E_i	Input voltage of the operational amplifier.
E_o	Output voltage of the operational amplifier.
R_L	Load resister.
K_1	Maximum amplitude of B.
T	Period of B.
f_B	Frequency of B.
a_n	The n^{th} Fourier cosine coefficient of the Fourier series of B.
b_n	The n^{th} Fourier sine coefficient of the Fourier series of B.
ω_B	The frequency of B expressed in radians, $f_B = \frac{\omega_B}{2\pi}$
$B_K(t)$	The K^{th} term of the Fourier series of B.
f_A	Frequency of A.
K_2	Maximum amplitude of A.
$V_m(t)$	The m^{th} term of the Fourier series of V_o.
N_m	The m^{th} Fourier cosine coefficient of the Fourier series of V_o.
ω_A	The frequency of A expressed in radians, $f_A = \frac{\omega_A}{2\pi}$

7.6 Introduction

In the conversion and analysis of active sonar data, it is often desirable to up or down shift the frequency spectrum of analog data to a more easily handled band. One method of doing this is to use an analog multiplier to heterodyne the signal. However, this method has the disadvantages of non-linearity, sensitivity to thermal changes and high cost. The above difficulties may be overcome by using a switching modulator. This device multiplies the input data signal by a square wave of any chosen frequency. The output of the modulator can then be passed through a bandpass filter to select the upper or lower sideband of the heterodyned signal. The filter output will be an up or down shifted version of the input signal.

7.7 Description of the Modulator

7.6.1 BASIC OPERATION

Basically, the modulator consists of an inverting amplifier with a gain of -1, a non-inverting amplifier with a gain of 1, and a transistor switch as shown in figure 15. The outputs A and $\bar{A}$ of the amplifiers are selected by the switch at a rate determined by the

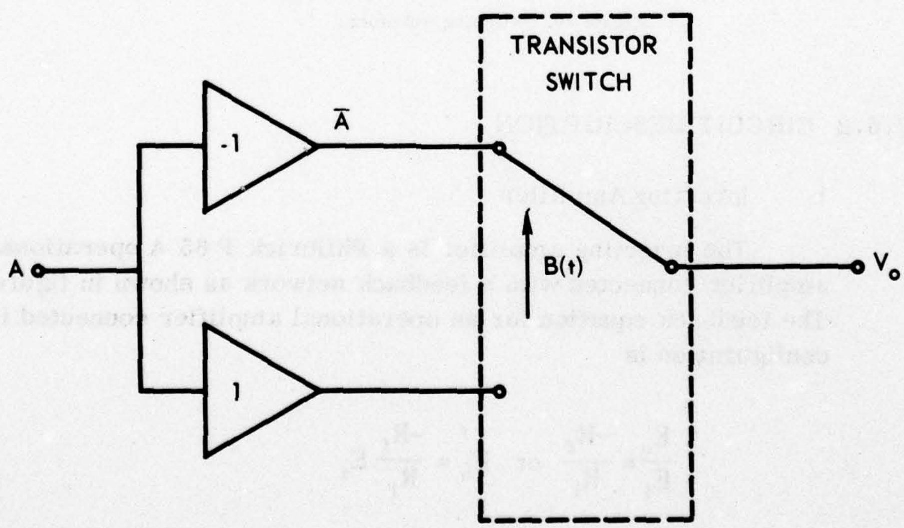


Figure 15. Modulator block diagram.

square wave switching waveform B. If B is as shown in figure 16 with period T, then from $t = \frac{-T}{4}$ to $t = \frac{T}{4}$ the switch selects the non-inverting amplifier and $V_o(t) = KA(t)$. From $t = \frac{T}{4}$ to $t = \frac{3T}{4}$, the switch selects the inverting amplifier and $V_o(t) = K\bar{A}(t)$. The resulting waveform, V_o, can then be expressed as

$$V_o(t) = K(A(t) \times B(t)) \tag{1}$$

the time multiplication of A and B where K is a constant scaling factor.

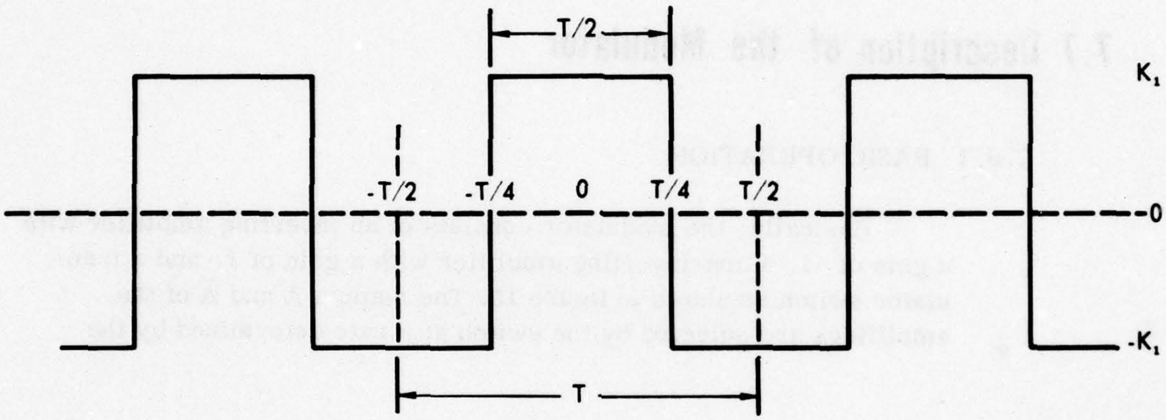


Figure 16. Switching waveform.

7.6.2 CIRCUIT DESCRIPTION

1. Inverting Amplifier

The inverting amplifier is a Philbrick P 65 A operational amplifier connected with a feedback network as shown in figure 17. The feedback equation for an operational amplifier connected in this configuration is

$$\frac{E_o}{E_i} = \frac{-R_f}{R_i} \quad \text{or} \quad E_o = \frac{-R_f}{R_i} E_i$$

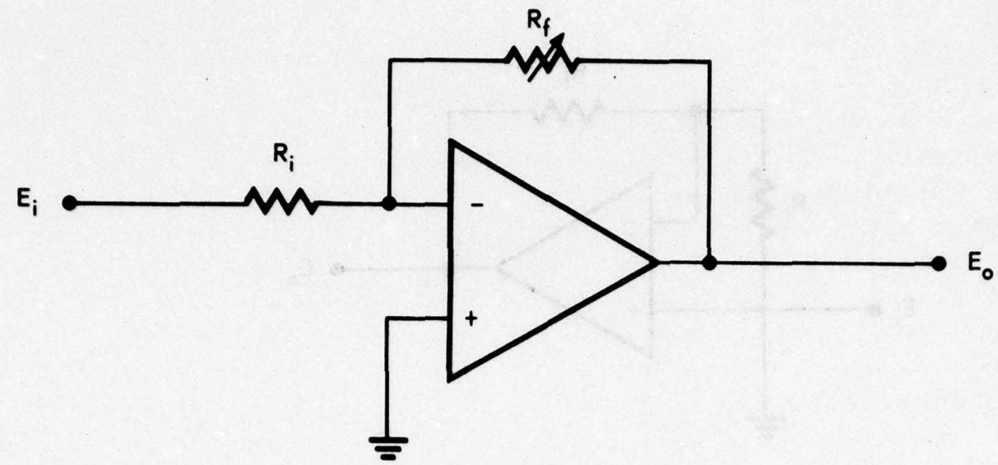


Figure 17. Inverting amplifier.

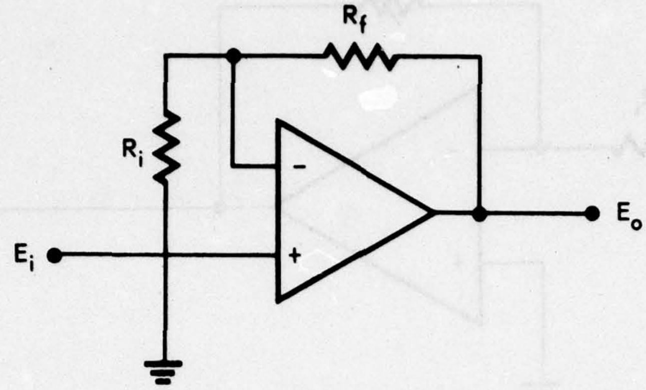
When the potentiometer in the feedback branch is adjusted so that $R_f = R_i = 10K\Omega$ this reduces to

$$E_o = -E_i \text{ or } \bar{A} = -A. \tag{2}$$

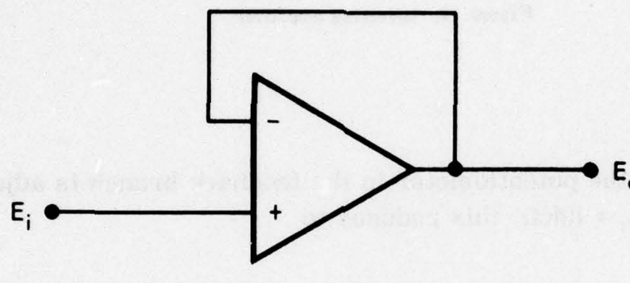
The resistors shown are ±1%; and the offset of the operational amplifier is adjusted so that when $A = 0$, $\bar{A} = 0$.

2. Non-inverting Amplifier

The non-inverting amplifier is another P 65 A operational amplifier connected as a special case of the feedback network shown in figure 18 a). The feedback equation for this network is $\frac{E_o}{E_i} = \frac{R_i + R_f}{R_i}$ or $E_o = \frac{R_i + R_f}{R_i} E_i$. For the non-inverting amplifier used in the modulator, figure 18 b), R_i is an open circuit and R_f is a short circuit (i.e., $R_i = \infty$, $R_f = 0$) so that the equation reduces to $E_o = E_i$. The offset of this amplifier is also adjusted to zero.



a) Non-inverting amplifier



b) Special case of the non-inverting amplifier.

Figure 18. Non-inverting amplifier and special case of the non-inverting amplifier.

3. Transistor Switch

To provide the switching function, the circuit shown in figure 19 was developed, where Q1, Q2 and Q3 are pnp germanium transistors (2N1305's). Q3 operates as an inverter, supplying a switching waveform which is 180° out of phase with B to the base of Q2. Therefore, when B is negative, Q1 is on, and Q2 is off and the output can be determined by the simplified circuit of figure 20. Therefore, the output can be stated as

$$V_o(t) \approx \frac{R_L \,||\, 10^5}{10^5 + R_L \,||\, 10^5}\,\bar{A}(t) = \frac{\dfrac{10^5 \cdot R_L}{10^5 + R_L}\,\bar{A}(t)}{10^5 + \dfrac{10^5\, R_L}{10^5 + R_L}} = \frac{R_L}{10^5 + 2R_L}\,\bar{A}(t) \qquad (3)$$

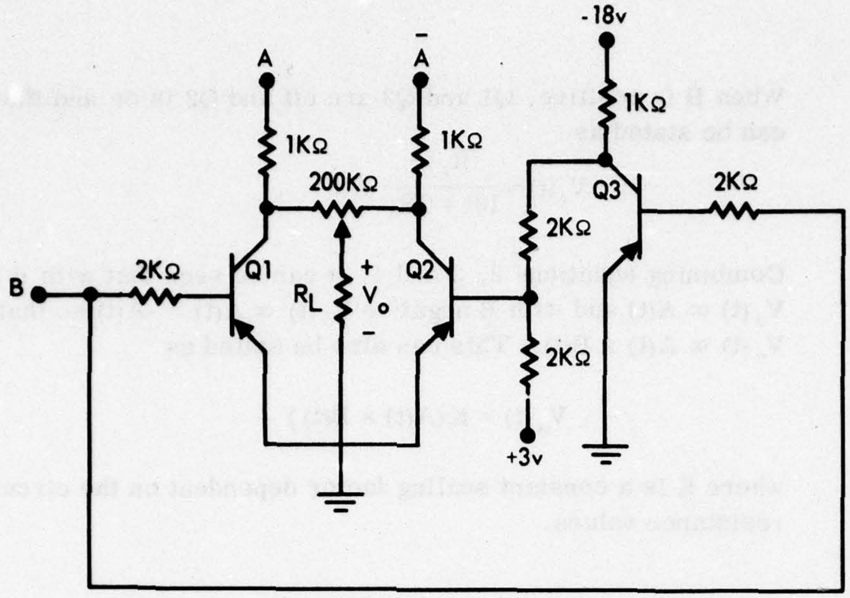


Figure 19. Transistor switch.

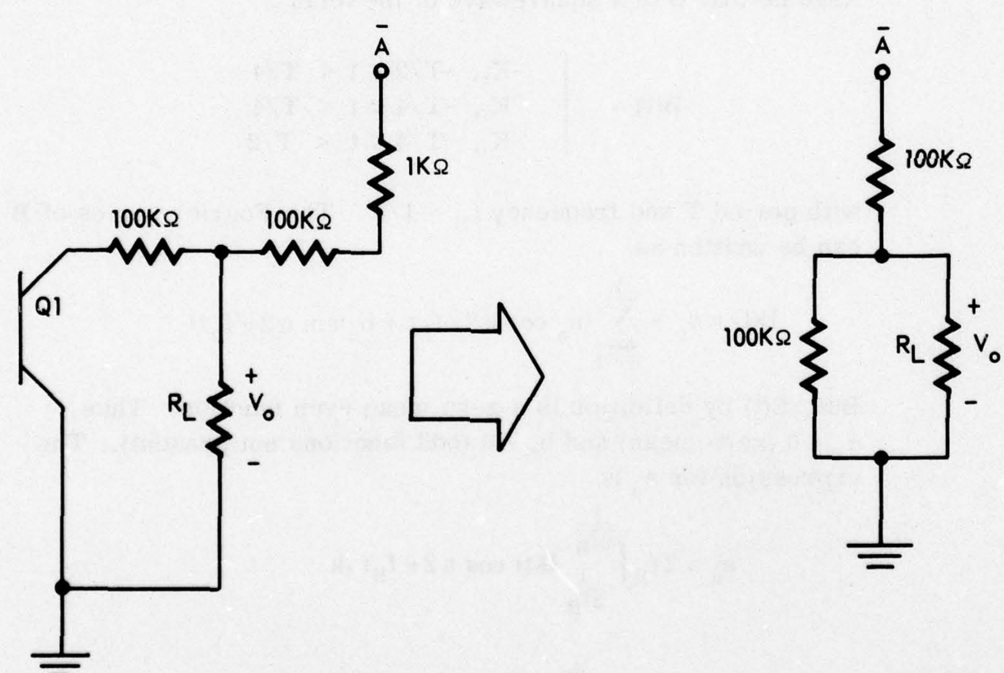


Figure 20. Simplified circuit model with B negative.

When B is positive, Q1 and Q3 are off and Q2 is on and the output can be stated as

$$V_o(t) \approx \frac{R_L}{10^5 + 2R_L} A(t) \qquad (4)$$

Combining equations 2, 3 and 4, it can be seen that with B positive $V_o(t) \propto A(t)$ and with B negative $V_o(t) \propto \bar{A}(t) = -A(t)$ so that $V_o(t) \propto A(t) \times B(t)$. This can also be stated as

$$V_o(t) = K(A(t) \times B(t)) \qquad (5)$$

where K is a constant scaling factor dependent on the circuit resistance values.

7.6.3 THEORETICAL OUTPUT SPECTRUM

Assume that B is a squarewave of the form

$$B(t) = \begin{cases} -K_1, & -T/2 < t < -T/4 \\ K_1, & -T/4 < t < T/4 \\ -K_1, & T/4 < t < T/2 \end{cases}$$

with period T and frequency $f_B = 1/T$. The Fourier series of B can be written as

$$B(t) = a_o + \sum_{n=1}^{\infty} (a_n \cos n 2\pi f_B t + b_n \sin n 2\pi f_B t)$$

But, B(t) by definition is a zero mean even function. Thus, $a_o = 0$ (zero mean) and $b_n = 0$ (odd functions not present). The expression for a_n is

$$a_n = 2f_B \int_{-\frac{1}{2f_B}}^{\frac{1}{2f_B}} B(t) \cos n 2\pi f_B t \, dt$$

Let $y = n 2\pi f_B t$ and $\frac{dy}{n 2\pi f_B} = dt$, then

$$a_n = \frac{1}{n\pi} \int_{-\pi n}^{-\frac{\pi n}{2}} (-K_1) \cos y \, dy + \frac{1}{n\pi} \int_{-\frac{\pi n}{2}}^{\frac{\pi n}{2}} K_1 \cos y \, dy + \frac{1}{n\pi} \int_{\frac{\pi n}{2}}^{\pi n} (-K_1) \cos y \, dy$$

$$a_n = \frac{2K_1}{n\pi}\int_0^{\frac{\pi n}{2}} \cos y \, dy - \frac{2K_1}{n\pi}\int_{\frac{\pi n}{2}}^{\pi n} \cos y \, dy$$

$$= \frac{2K_1}{n\pi}\left\{ \sin y \Big|_0^{\frac{\pi n}{2}} - \sin y \Big|_{\frac{\pi n}{2}}^{\pi n} \right\}$$

$$= \frac{2K_1}{n\pi}\left\{ \sin \frac{\pi n}{2} - \sin 0 - \sin \pi n + \sin \frac{\pi n}{2} \right\}$$

$$= \frac{4K_1}{n\pi} \sin \frac{\pi n}{2}$$

therefore,

$$a_n = \begin{cases} 4K_1/n\pi, & n = 1, 5, 9, \ldots, 4K+1, \ldots \\ -4K_1/n\pi, & n = 3, 7, 11, \ldots, 4K+3, \ldots \\ 0, & n = \text{even integers} \end{cases}$$

Thus, the Fourier series of B is

$$B(t) = \frac{4K_1}{\pi}\{\cos(2\pi f_B t) - \tfrac{1}{3}\cos[3(2\pi f_B t)] + \tfrac{1}{5}\cos[5(2\pi f_B t)] - \tfrac{1}{7}\cos[7(2\pi f_B t)] + \ldots\} \quad (6)$$

which can be written in exponentials as

$$B(t) = \frac{4K_1}{2\pi}[(e^{j\omega_B t} + e^{-j\omega_B t}) - \tfrac{1}{3}(e^{j3\omega_B t} + e^{-j3\omega_B t}) + \tfrac{1}{5}(e^{j5\omega_B t} + e^{-j5\omega_B t}) - \ldots]$$

where $\omega_B = 2\pi f_B$ and the K^{th} term of B(t) is

$$B_k(t) = \frac{4K_1(-1)^k}{2(2K-1)\pi}[e^{j(2k-1)\omega_B t} + e^{-j(2k-1)\omega_B t}] \quad (7)$$

Now assume A to be a pure consinusoid of frequency f_A. A(t) can then be written as

$$A(t) = K_2 \cos 2\pi f_A t = \frac{K_2}{2}(e^{j\omega_A t} + e^{-j\omega_A t}) \quad (8)$$

where $\omega_A = 2\pi f_A$. The m^{th} term of $V_o(t)$,

where $V_o(t) = K(A(t) \times B(t))$, is therefore:

$$V_m(t) = K(A(t) \times B_m(t))$$

$$= K \cdot \frac{K_2}{2} \cdot \frac{4K_1(-1)^m}{2\pi(2m-1)} \cdot (e^{j\omega_A t} + e^{-j\omega_A t})$$

$$\times (e^{j(2m-1)\omega_B t} + e^{-j(2m-1)\omega_B t})$$

$$= \frac{N_m}{2}(-1)^m \{e^{j[(2m-1)\omega_B + \omega_A]t} + e^{-j[(2m-1)\omega_B + \omega_A]t}$$

$$+ e^{j[(2m-1)\omega_B - \omega_A]t} + e^{-j[(2m-1)\omega_B - \omega_A]t}\}$$

$$= N_m(-1)^m \{\cos[(2m-1)\omega_B + \omega_A]t + \cos[(2m-1)\omega_B - \omega_A]t\}$$

$$= N_m(-1)^m \{\cos 2\pi[(2m-1)f_B + f_A]t + \cos 2\pi[(2m-1)f_B - f_A]t\}$$

where $N_m = \dfrac{2 \cdot K \cdot K_1 \cdot K_2}{\pi(2m-1)}$

Note (fig. 21) that the spectrum of $V_o(t)$ contains the sidebands which are $\pm f_A$ about the fundamental frequency and about the harmonics of B, but does not contain f_B, its harmonic frequencies, or f_A.

7.8 Test Results

The performance of the modulator was tested by choosing $f_A = 400$ Hz and $f_B = 1$ kHz and displaying the results with a Nelson-Ross model 021 spectrum analyzer plug-in unit in a Tektronix 564-A oscilloscope. The resulting waveforms and spectrum are shown in the pictures at the end of this section. Figure 22 is a display of V_o, the switched waveform that is the output of the modulator. In figure 23, the spectrum of B, the 1 kHz squarewave switching waveform with the fundamental frequency and the odd harmonics, is displayed in a linear plot of signal amplitude. Figure 24 is a plot of the 400 Hz sum and difference frequencies that make up the spectrum of V_o. Figure 25 is an overlay of the 400 Hz sum and difference frequencies on the spectrum of B. The amplitudes in figures 24 and 25 are plotted logarithmically.

By displaying the spectrum of $A \times B$ with the spectrum analyzer and increasing its gain, it was found that the carrier rejection is approximately -30 dB with respect to the amplitude of the sidebands about the 1 kHz fundamental frequency. This measurement is inexact due to the difficulty in obtaining sufficient sensitivity without instability in the trace. The signal to noise ratio is approximately 33 dB. The voltage transfer ratio with A = 1 v peak-to-peak and B = ±3 v is

$$VTR = \frac{|V_o|}{|A|} \approx \frac{50\text{ mv}}{1\text{ v}} = .05$$

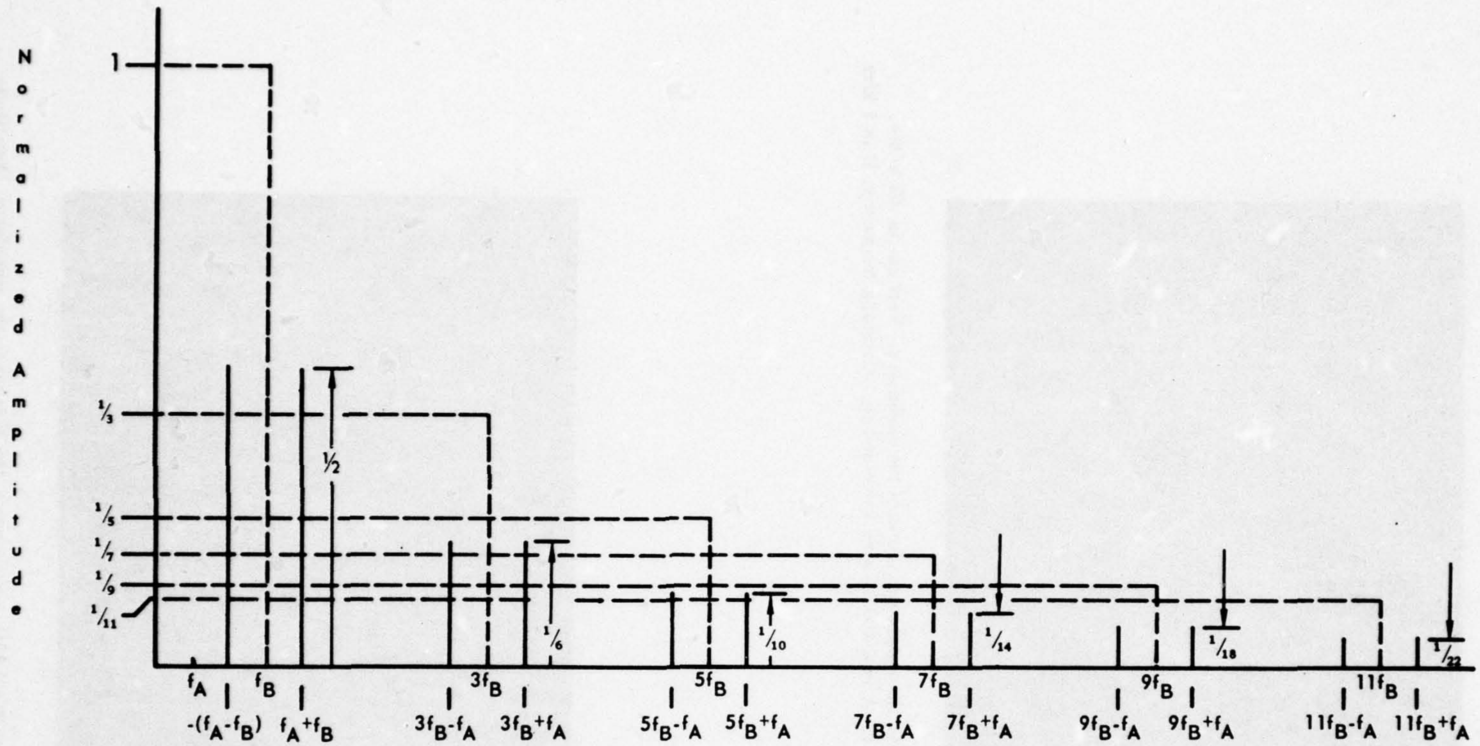


Figure 21. Theoretical spectrum of V_o.

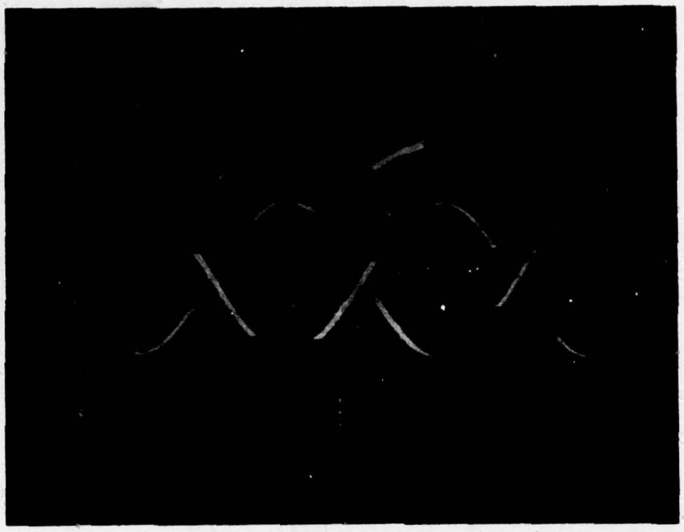


Figure 22. $V_o = K(A \times B)$, the output waveform of the modulator. Vertical is .02 v/div. Horizontal is .5 msec/div. A is a 400 Hz sine wave and the switching frequency, B is 1 kHz.

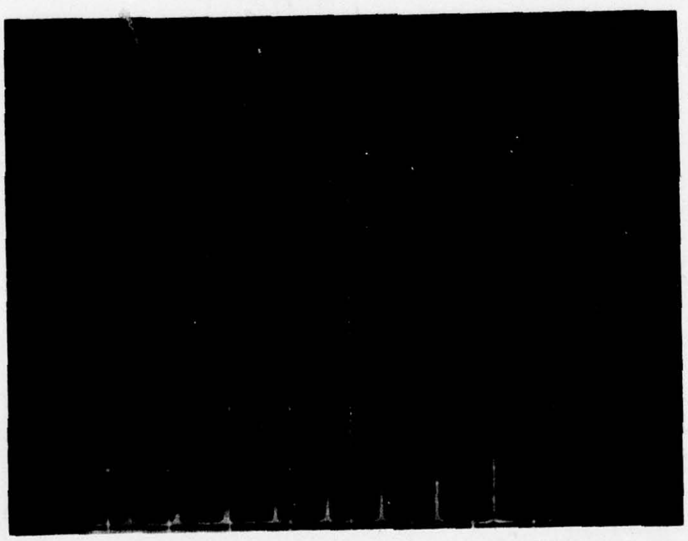


Figure 23. The spectrum of a 1 kHz square wave, the B input to the modulator. Amplitude is plotted linearly.

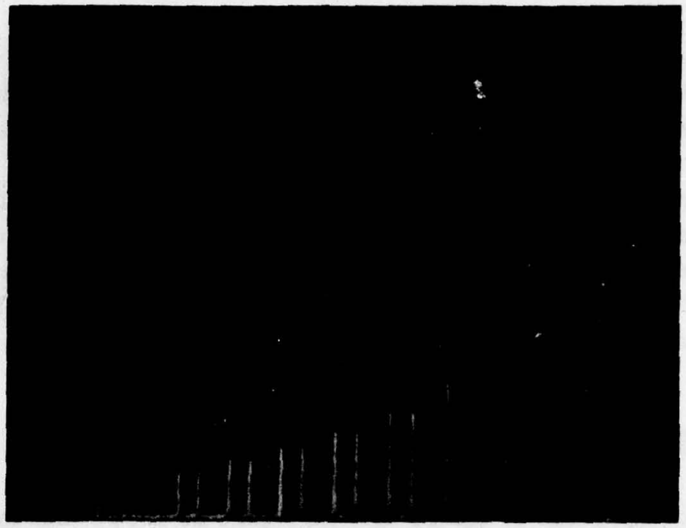


Figure 24. Spectrum of V_o, the output of the modulator, showing the 400 Hz sum and difference frequencies. Logarithmic plot, vertical is 2.5 dB/div.

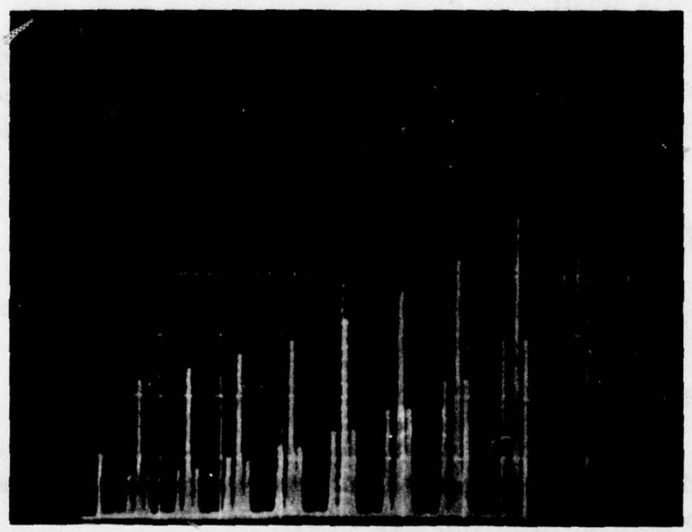


Figure 25. Overlay of the spectrums of B and V_o showing fundamental and odd harmonics of the 1 kHz square wave and the 400 Hz sum and difference frequencies of the modulator output.

The modulator will operate for voltage ranges from 2 mv peak-to-peak to 10v peak-to-peak. At higher input levels, some clipping occurs due to the input characteristics of the operational amplifiers.

The use of an unsymmetrical switching waveform causes the appearance of even harmonics and a degradation of the carrier rejection. Other causes of carrier rejection degradation were found to be the presence of D. C. offset at the output of the operational amplifiers and slow switching speeds of the transistors used.

7.9 Conclusions

1. A comparison of figure 20 with figure 25 shows that the described modulator closely approximates the mathematical model described in the section on the theoretical output spectrum.

2. Since the transistor switches are being driven to cutoff and to saturation, the non-linearities of the transistors have no effect on the operation of the modulator.

3. For the same reason, the sensitivity to thermal change is very slight.

4. Since standard components are used, the overall price of the modulator is small.

5. It can be concluded, therefore, that the use of a switching modulator is a practical method of up or down shifting the frequency spectrum of analog data which eliminates several of the drawbacks of multipliers.

7.10 Recommendations

1. This device should be useful in shifting the frequency of analog sonar data to a band more convenient for study.

2. Further study is indicated in the following directions:

   a. extending the useful range of the modulator by adding an additional stage to cancel the Third Harmonic side bands of the modulating signal (see Appendix),

   b. increasing the switching speed by using F. E. T. 's,

c. **increasing the symmetry of the switching waveform by the use of Flip-flops,**

d. **investigating the requirements of the filters to be used to extract the desired band of frequencies.**

7.11 Appendix: Cancellation of Sidebands About the Third Harmonic

When f_A is approximately equal to f_B, a difficulty arises in distinguishing the upper sideband of the fundamental frequency from the lower sideband of the third harmonic. This section describes a possible method of eliminating this difficulty. The method calls for including an additional switching modulator operating at 3 times the switching frequency of the original circuit. Scaling the output of the additional modulator by 1/3 and summing with the output of the original modulator, the sidebands of the $3K^{th}$ ($K = 1, 3, 5, \ldots$) harmonics of V_o should be eliminated (see figure 26). The feasibility of this process is demonstrated by the following mathematical development. Let B(t) be the following:

$$B(t) = \begin{cases} -1, & -\frac{1}{2f_B} < t < -\frac{1}{4f_B} \\ -1, & -\frac{1}{4f_B} < t < \frac{1}{4f_B} \\ -1, & \frac{1}{4f_B} < t < \frac{1}{2f_B} \end{cases}$$

The Fourier series of this is described in equation 6 as

$$B(t) = \frac{4}{\pi}\{\cos 2\pi f_B t - \frac{1}{3}\cos 2\pi (3 f_B) t + \frac{1}{5}\cos 2\pi (5 f_B) t - \frac{1}{7}\cos 2\pi (7 f_B) t + \ldots\}$$

Now let C(t) be the same as B(t), but with a frequency of $3 f_B$. Then

$$C(t) = \frac{4}{\pi}\{\cos 2\pi (3 f_B) t - \frac{1}{3}\cos 2\pi (9 f_B) t + \frac{1}{5}\cos 2\pi (15 f_B) t - \ldots\}$$

By summing B(t) with 1/3 C(t), the result is

$$B(t) + \frac{1}{3}\ C(t) = \frac{4}{\pi}\{\cos 2\pi\ f_B t + \frac{1}{5}\ \cos 2\pi\ (5 f_B)\ t - \frac{1}{7}\cos 2\pi\ (7 f_B)\ t - \frac{1}{11}\cos 2\pi\ (11 f_B) t + \ldots\}$$

and the third harmonic has been eliminated.

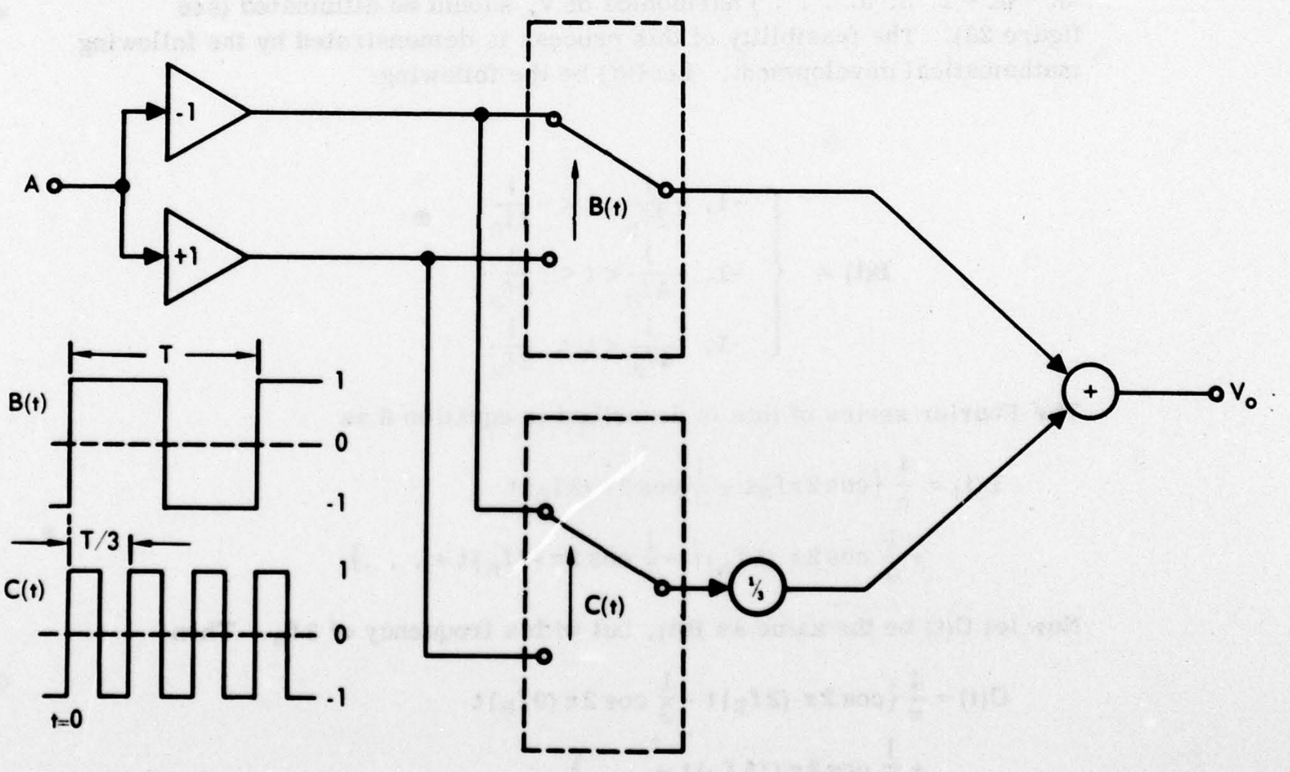


Figure 26. Cancellation of sidebands about the third harmonic.

7.12 References

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SECTION 8

APPENDIX II: SECTIONS 3.5 AND 3.6 OF NEL SPECIFICATION NO. 3180-66-6 (ACTIVE SONAR DATA ANALYSIS AND CONVERSION SYSTEM)

3.5 Heterodyne Unit

The Contractor shall provide four (4) of the Heterodyne units specified herein. NEL approval of the design is required (see section 6.1).

3.5.1 General

The heterodyning unit (HU) produces an output signal which has a spectrum identical with that of the input signal but shifted downward in frequency. A simplified block diagram of the HU showing the three modes of HETERODYNE, HETERODYNE NO-FILTER, and DIRECT, and the frequency relationships is shown in Figure 2. (Note that the input and output buffer amplifiers, described in section 3.3 are patched-in, thereby allowing use of the buffer amplifiers for purposes other than heterodyning. From a functional viewpoint, the buffer amplifiers are to be considered an integral part of the HU whenever the HU is being discussed.) The heterodying is accomplished as follows. First, the input signal is passed through a buffer amplifier which gives a high impedance and good common mode rejection. The signal is then multiplied by a fixed-frequency square wave in a switching type balanced mixer. The mixer output consists of the downward frequency shifted signal, an upward frequency shifted signal, and various higher frequency harmonics related to the switching frequency and to the signal frequencies. A low-pass filter, having three switch selectable bandwidths, rejects all of these outputs except the down-shifted signal, which passes through a buffer amplifier and appears at the output. The external oscillator described in section 3.6 is used to supply the heterodyning frequency to downward-shift the input signal spectrum.

3.5.2 Detailed Specifications

3.5.2.1 Inputs

3.5.2.1.1

As shown in Figure 2, the signal input to the heterodyne unit is the input to the buffer amplifier. Thus, the HU shall accept inputs as in section 3.3.1 dealing with "buffer amplifier inputs" with the exception that the frequency range shall be from 0 c/sec (DC) to 20 K c/sec.

3.5.2.1.2

The HU shall accept signals as defined in the following table ("bandwidth" is defined as the minimum width of a frequency band centered at f_o outside of which there is no signal energy).

Class	Maximum Bandwidth	Center Frequency
H1	300 cps ($f_o \pm 150$ cps)	1000-2000 cps
H2	600 cps ($f_o \pm 300$ cps)	2000-4000 cps
H3	1200 cps ($f_o \pm 600$ cps)	4000-8000 cps
N	All signals which do not belong to H1, H2, or H3 but which are limited to ± 10 volts and have frequency components below 20,000 c/sec.	

3.5.2.1.3 External Oscillator Input

a. The HU's external oscillator input shall accept the square wave supplied by the square wave oscillator described in section 3.6.

b. Additionally, the input impedance shall be greater than 1.0 megohms shunted by less than 50 pf.

3.5.2.2 Outputs

As shown in Figure 2, the signal output from the HU depends on the chosen mode, and the output characteristics of the buffer amplifier.

3.5.2.2.1 <u>Heterodyne Mode</u>

3.5.2.2.1.1

The HU output signal shall be a downward frequency-shifted version of the input signal amplified by the gain of the buffer amplifiers. The signals which are to be heterodyned are those of classes H1, H2, and H3 (see section 3.5.2.1.2). The external oscillator frequency will always be 200 cycles below the center frequency f_o for class H1 signals, 350 cycles below f_o for class H2 signals, and 650 cycles below f_o for class H3 signals. Thus, the spectrum of the output will be centered at 200 cps, 350 cps, and 650 cps for class H1, H2, and H3 signals respectively. The output spectrum will be non-inverted because the heterodyning frequency is less than f_o.

3.5.2.2.1.2

The HU shall be designed so that if the input is

$$\sum a_n \sin(\omega_n t + \varphi_n)$$

and the oscillator input is a square wave given by

$$\sum \frac{4}{(2n-1)\pi} \sin(2n-1)\omega_c t$$

then the output shall be

$$A \sum_{n=1}^{K} a_n \cos\{(\omega_n - \omega_c)t + \varphi_n\}$$

where A is the gain factor of the buffer amplifiers. The output filters which are used in the HETERODYNE mode will cause a slight departure from this input-output relationship. (The maximum permissible departure is given in sections 3.5.2.2.1.5 and 3.5.2.2.1.6.)

3.5.2.2.1.3

The output of the switching-type balanced mixer shall be passed through a low-pass filter having three switch selectable bandwidths.

Normally the narrowest bandwidth, denoted by B1, will be used only for type H1 signals; B2 for type H2 signals; and B3, the highest bandwidth, for type H3 signals.

3.5.2.2.1.4

The frequency response will be tested in the following manner. Assume that the B1 filter is used. A sine wave with a peak amplitude of one half of full scale will be applied to the input terminals. The frequency will be slowly swept from f_o - 150 c/sec to f_o + 150 c/sec where f_o is any frequency between 1 and 2 Kc/sec. (The proper heterodyning frequency of f_o - 200 c/sec will be supplied.) The amplitude of the sine wave output as a function of frequency will be recorded. A similar test will be run using the B2 filter and sweeping from f_o - 300 c/sec to f_o + 300 c/sec where f_o lies between 2 and 4 Kc/sec. A third test will be run using the B3 filter and sweeping from f_o - 600 to f_o + 600, where f_o lies between 4 and 20 Kc/sec.

3.5.2.2.1.5

The output amplitude shall deviate less than 1% from the nominal output obtained by multiplying the input level by the gain setting. (The tests of section 3.5.2.2.1.4 will be used.)

3.5.2.2.1.6

The test for phase linearity will be conducted exactly as above except that the phase of the output will be monitored instead of the amplitude. The input signal can be represented by a sin $(\omega t + \varphi)$ over a period of time which is short compared to the time it takes to sweep the entire bandwidth. Here, "a" is a constant equal to half of full scale. If the external oscillator waveform is

$$\sum_{n=1}^{\infty} \frac{4}{(2n-1)\pi} \sin(2n-1)\,\omega_c t$$

then the corresponding output should be 1/2 $\cos\{(\omega - \omega_c)t + \varphi\}$ if the filter had no phase shift. However, the filter will have some phase shift φ' so that the measured output is 1/2 $\cos\{(\omega - \omega_c)t + \varphi'\}$. The quantity $\varphi - \varphi'$ will be plotted as a function of the input frequency ω as ω is varied from the lower band edge to the upper band edge. The phase deviation from a linear phase characteristic shall be less than 3 degrees over the entire band. [There are three tests, one for each filter].

3.5.2.2.1.7

The linearity test will be conducted by heterodyning a fixed frequency sine wave input. The p-p amplitude of the input will be varied from zero to full scale at the maximum gain setting of the buffer amplifier, and the p-p output amplitude as a function of the input amplitude will be recorded. The deviation of the output amplitude from a linear relationship shall be less than .05% of full scale. This specification applies for all input frequencies provided that they are heterodyned to a frequency within the bandwidth of the output filters.

3.5.2.2.2 Direct Mode

The HU output shall be the input signal amplified by the gain of the buffer amplifiers. No heterodyning shall occur nor shall the signal be filtered. In this mode, all classes of input signals will be used (classes H1, H2, H3, and N) and the HU must have response to dc. Since the two buffer amplifiers are in cascade in this mode, the output signal characteristics are described in section 3.3.2.

3.5.2.2.3 Heterodyne No-Filter Mode

The output filter shall be bypassed and the output of the balanced mixer shall be fed directly through the buffer amplifier to the output. Except for the above differences, operation shall be the same as in the HETERODYNE Mode. The output signal shall be an amplified non-inverted version of the input signal, the polarity of which is alternately reversed at the frequency of the external oscillator.

3.5.2.3 Low Pass Output Filters

3.5.2.3.1

The output filters shall have three switch selectable bandwidths. (Three separate filters selected by a switch may be used if necessary.) Here "bandwidth" does not refer to the 3 dB down frequency but instead refers to the maximum bandwidth of the signal with which the filter will be used. (The 3 dB bandwidth will be determined by the spurious frequency rejection specified in section 3.5.2.3.2.) The table below gives the basic filter data.

Filter	B1	B2	B3
Operating Passband	50-350 c/sec	50-650 c/sec	50-1350 c/sec
Operating Bandwidth	300 c/sec	600 c/sec	1200 c/sec
Used with Input Signal of Class	H1	H2	H3

3.5.2.3.2

The B1 filter shall be designed so that when any type H1 signal is being heterodyned, the rms value of all spurious responses and noise above 350 cps is more than 60 dB below the rms value of a full scale sine wave output (7.07 volts rms). The B2 and B3 filters shall likewise meet these requirements above 650 and 1250 cps respectively, assuming that type H2 and H3 signals are being heterodyned.

3.5.2.4 DC Drift

In all modes, the DC drift measured at the buffer amplifier output shall be less than 5.0 millivolts when the signal source impedance is less than 1,000 ohms.

3.5.2.5 Controls

3.5.2.5.1

A four position mode switch shall be supplied on the front panel. The switch positions are HETERODYNE, HET-NO FILTER, DIRECT, and PWR-OFF. When the mode switch is in the PWR-OFF position, the power shall be disconnected.

3.5.2.5.2

A front panel three position Filter Bandwidth switch shall be provided. The three positions shall be labelled 300, 600, and 1200.

3.5.2.6 Connectors

3.5.2.6.1 A two-terminal signal input connector shall be provided with one terminal connected to either an internal ground or chassis ground. This connector shall mate with the output connector of the buffer amplifier. This connector shall be at the rear of the HU.

3.5.2.6.2

Two (2) two-terminal coaxial type signal connectors shall be provided at the rear of the HU with the shield connection returned to chassis ground. One shall be used for signal output, the other for external oscillator input.

3.5.2.6.3

Additionally, all input-output connectors shall be available at the patch panel.

3.6 Square Wave Oscillator

The Contractor shall provide one (1) square wave oscillator as specified herein.

3.6.1 General

An external square wave oscillator shall be provided to supply the heterodyne units with the proper heterodyning frequency. In this manner, input signals to the heterodyne units centered from 1.0 K c/sec to 18 K c/sec may be downward frequency shifted to the pass-band of the low-pass filter.

3.6.2 Characteristics

The external oscillator shall have the following characteristics:

a. Square wave output continuously variable in the frequency range from at least 800 c/sec to 20,000 c/sec.

b. Amplitude of square wave variable with a maximum of ± 10 volts (peak) and a nominal value of ± 2 volts (peak).

c. Rise and fall times less than 100 nanoseconds.

d. Symmetry factor of square wave less than .005 (defined as the difference between two adjacent half period amplitudes divided by their sum).

e. Frequency of square wave crystal controlled and stability better than .001% of the nominal value.

f. Output single ended returned to ground.

3.6.3 Connectors

A two-terminal coaxial type signal output connector shall be provided at the patch panel, with the shield connection returned to chassis ground. There shall be at least four output hubs on the patch panel for connecting to four heterodyne units.

3.6.4

The Contractor shall consider using a general purpose signal generator capable of supplying other signal types in addition to the square waves specified."

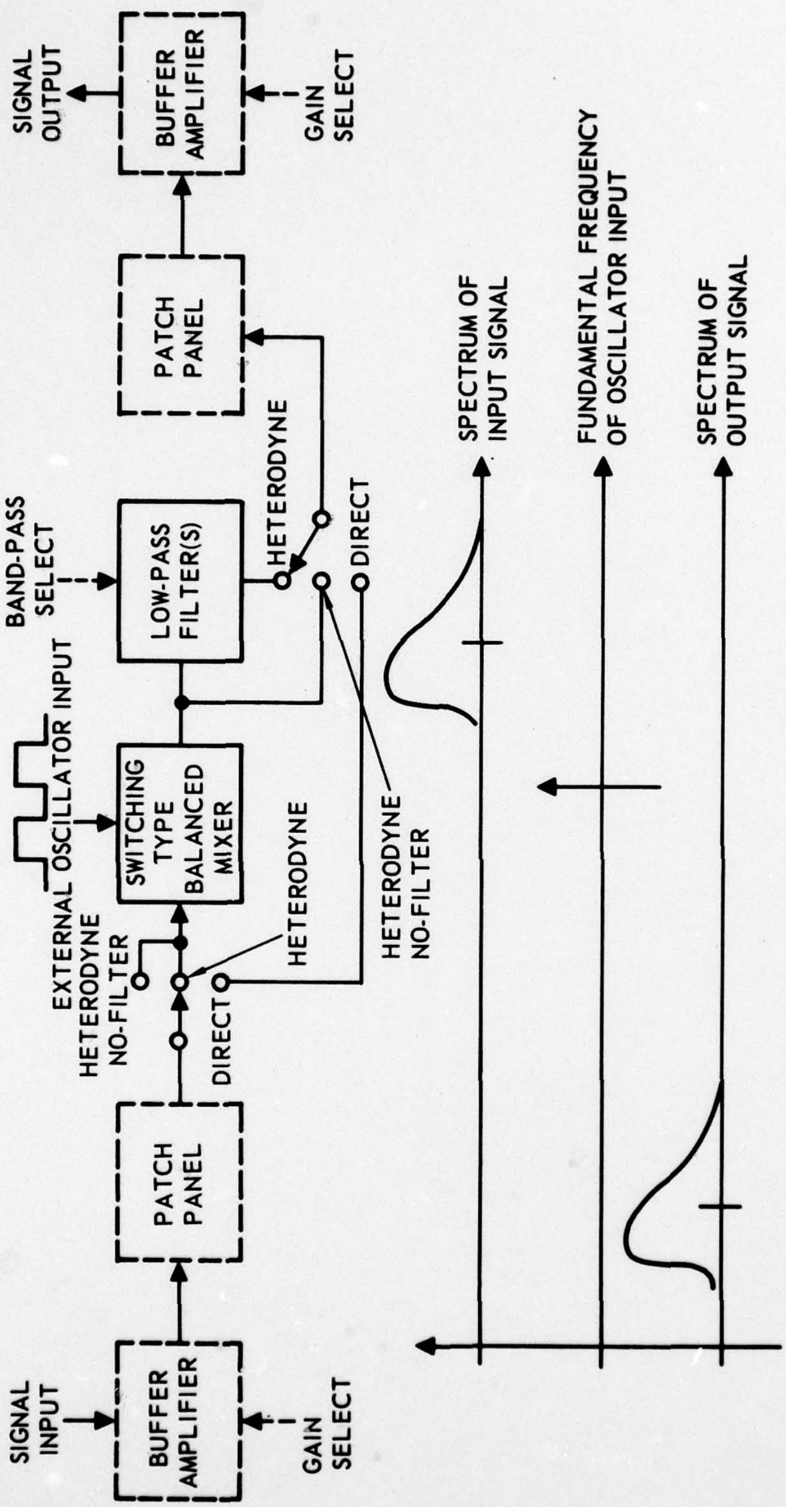

Figure 2. Heterodyner and signal spectrum.

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